

# $\Lambda(1405)$ and kaonic few-body states in chiral dynamics

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**Abstract.** The present status of the  $\Lambda(1405)$  structure study in chiral dynamics is briefly reviewed. It turns out that the  $\Lambda(1405)$  resonance can be described by hadronic dynamics. The idea of the hadronic molecular state is extended to kaonic few-body states. It is concluded that, due to the fact that  $K$  and  $N$  have similar coupling nature in  $s$ -wave  $\bar{K}$  couplings, there are few-body quasibound states with kaons systematically just below the break-up thresholds, like  $\bar{K}NN$ ,  $\bar{K}KN$  and  $\bar{K}KK$ , as well as  $\Lambda(1405)$  as a  $\bar{K}N$  quasibound state and  $f_0(980)$  and  $a_0(980)$  as  $\bar{K}K$ .

**Keywords:** chiral dynamics,  $\Lambda(1405)$ , kaonic few-body systems

**PACS:** 14.20.-c, 12.39.Fe, 14.40.Df

## INTRODUCTION

Searching out effective constituents in the structure of hadrons is a clue to understand strongly interacting systems. Certainly, quarks and gluons are the fundamental constituents of hadrons, but the current quarks appearing in the QCD Lagrangian cannot be effective degrees of freedom to describe the hadron structure in simple and intuitive ways. Constituent quark models give a simple picture of the baryon structure, reproducing the magnetic moments of the low-lying octet baryons by group theoretical argument and also their masses by the Gell-Mann–Okubo mass formula, which is a consequence of the flavor SU(3) with its small breaking by the quark masses. The success of the constituent quark models indicates that the symmetry of quark is realized in the baryon structure through the constituent quarks. In contrast, baryon resonances are decaying particles into mesons and a baryon by strong interaction, and thus it is natural that baryon resonances may have large hadronic components apart from quark-originated components. Therefore, for the investigation of the baryon resonance structure, the aspect of hadron dynamics is unavoidable to be considered. In this paper, we discuss hadronic resonance states in term of chiral dynamics. First, we briefly review the present theoretical status of the  $\Lambda(1405)$  resonance, which is now to be considered as one of the typical examples of meson-baryon quasibound states. Then we further develop the idea of the hadronic quasibound state into few-body hadronic systems with kaons.

## THE STRUCTURE OF $\Lambda(1405)$

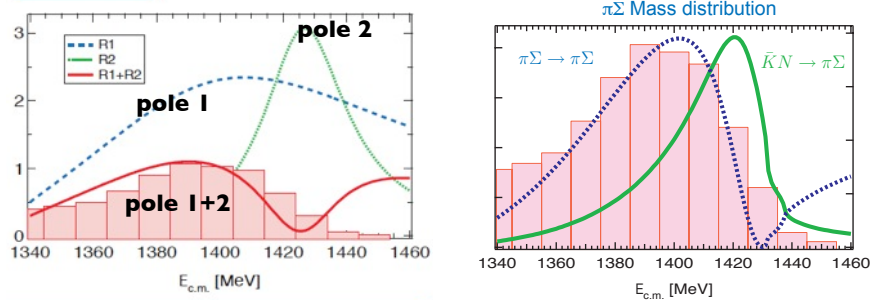
The  $\Lambda(1405)$  resonance is the lowest baryon with  $J^P = (1/2)^-$ . It is not easy to explain the light  $\Lambda(1405)$  mass and the  $LS$  splitting against  $\Lambda(1520)$  in simple quark models, once one determines the model parameters in the nucleon sector.  $\Lambda(1405)$  is located in

a 100 MeV window between the  $\pi\Sigma$  and  $\bar{K}N$  thresholds and the decay width of  $\Lambda(1405)$  is given by the open  $\pi\Sigma$  channel. Thus, for the study of the  $\Lambda(1405)$  structure, one needs dynamical description with coupled channels, at least, with the  $\bar{K}N$  and  $\pi\Sigma$  channels.

One of the powerful theoretical frameworks to describe hadronic resonances in hadron dynamics is the coupled-channels approach based on chiral dynamics, so-called chiral unitary model, in which the resonances are described in hadron-hadron scattering [1, 2]. The elementary interactions of the scattering system are introduced by the chiral effective Lagrangian, and scattering equation is solved in a way to keep the  $s$ -channel unitarity. For the  $s$ -wave meson-baryon scattering with  $S = -1$  and  $Q = 0$ , this approach successfully reproduces the total and differential cross sections of  $K^-p$  scatterings, and the  $\Lambda(1405)$  resonance is obtained as a dynamically generated object without introducing explicit pole terms [1, 3, 4].  $\Lambda(1405)$  was found also to be an almost purely hadronic object [5]. After reproducing the observed scattering quantities, the chiral unitary model can be used to investigate the structure and properties of the dynamically generated resonances. The mass and width is obtained as the pole position of the scattering amplitude and the coupling nature of the resonance is extracted from the residues of the pole.

One of the important consequence of the chiral unitary model for  $\Lambda(1405)$  is that the observed spectrum of  $\Lambda(1405)$  is composed by two resonance states having different coupling nature [6]. The two poles for  $\Lambda(1405)$  in chiral dynamics was found first in Ref. [4] and later its significance was discussed in Ref. [6]. One of the pole is located at  $1390 - 66i$  MeV with a strong coupling to the  $\pi\Sigma$  channel, while the other is at  $1426 - 16i$  MeV with a dominant coupling to the  $\bar{K}N$  channel [6, 7]. Although these two states appear definitely different positions in the complex plane, due to their closer masses and decay widths, their contributions to the  $\Lambda(1405)$  spectrum seen on the real axis are entangled and these two states cannot be seen separately in the  $\Lambda(1405)$  spectrum. What one can observe in experiments is interference of these two states (see the left panel of Fig. 1). As a result of the presence of the two states with the different nature of the meson-baryon couplings, the  $\Lambda(1405)$  spectrum depends on the initial channel of the  $\Lambda(1405)$  production [6]. For example, if the  $\Lambda(1405)$  resonance is created by the  $\bar{K}N$  channel, the higher pole gives more contribution to the spectrum than the lower pole. Consequently the resonance peak in the  $\pi\Sigma$  spectrum appears around 1420 MeV, as shown in the right panel of Fig. 1. This means that, since initial wight of the  $\pi\Sigma$  and  $\bar{K}N$  contributions to the  $\Lambda(1405)$  production is different in each reaction mechanism, the peak position can be different in each reaction. Thus, when one investigates the  $\Lambda(1405)$  properties from scattering experiments, it is extremely important to pin down the production mechanism of  $\Lambda(1405)$  in each experiment.

The evidence of the double pole structure of  $\Lambda(1405)$  is given by observing the peak position of the  $\Lambda(1405)$  spectrum initiated by the  $\bar{K}N$  channel, which will be at around 1420 MeV and be different from the resonance position observed in other experiments. Since  $\Lambda(1405)$  is sitting below the  $\bar{K}N$  threshold, one cannot produce  $\Lambda(1405)$  directly by the  $\bar{K}N$  channel. A recent work has shown that  $K^-d \rightarrow \Lambda(1405)n$  is a good reaction [8], in which kaon brings strangeness into the system and  $\pi\Sigma$  cannot be the initial state of  $\Lambda(1405)$  production. The theoretical calculation [8] has also shown that the  $\Lambda(1405)$  resonance is produced mostly in backward angles as a consequence of dominant contributions from the two-step reaction, and the  $\Lambda(1405)$  spectrum peaking at 1420 MeV is consistent with an old bubble chamber experiment of  $K^-d \rightarrow \pi^+\Sigma^-n$  [9].

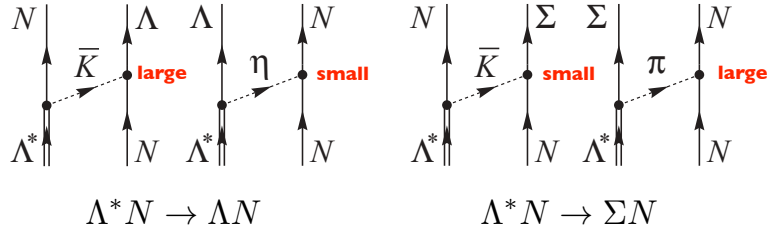


**FIGURE 1.** Mass spectra of  $\Lambda(1405)$  in arbitrary units [6]. The left panel shows the  $\pi\Sigma$  invariant mass spectrum (red line) of  $\pi\Sigma \rightarrow \pi\Sigma$  with  $I = 0$  calculated by the chiral unitary model together with the separated contributions of the lower and higher poles of  $\Lambda(1405)$ . The right panel shows a comparison of the  $\pi\Sigma$  spectra of  $\pi\Sigma \rightarrow \pi\Sigma$  and  $\bar{K}N \rightarrow \pi\Sigma$ . (The heights are adjusted.)

Further detailed experiments will be performed at J-PARC [10] and DAFNE. It is also worth to mention that, in  $K^-d \rightarrow Y\pi n$  reaction, since the resonance position of the  $\Lambda(1405)$  produced by  $\bar{K}N$  will be at 1420 MeV with a narrower width, one could have a chance to observe  $\Sigma(1385)$  and  $\Lambda(1405)$  as separated peaks in the missing mass spectrum of the emitted neutron [11].

The reason that there are two poles around the  $\Lambda(1405)$  energies is that the elementary meson-baryon interaction has two attractive channels, single and octet in the SU(3) flavor language or alternatively  $\bar{K}N$  and  $\pi\Sigma$  in the particle basis. It has turned out in Ref. [12] that  $\Lambda(1405)$  is essentially described by  $\bar{K}N$  and  $\pi\Sigma$ , and the  $\eta\Lambda$  and  $K\Xi$  channels give minor contributions to the  $\Lambda(1405)$  poles. In the single channel calculation there are a  $\bar{K}N$  bound state and a  $\pi\Sigma$  resonance in the  $\bar{K}N$  and  $\pi\Sigma$  channels, respectively, while with the  $\pi\Sigma$ - $\bar{K}N$  channel coupling, the  $\bar{K}N$  bound state obtains its decay width to the  $\pi\Sigma$  channel. Therefore, we conclude that the  $\Lambda(1405)$  resonance is described by the  $\bar{K}N$  bound state and the  $\pi\Sigma$  strong correlation. This is the meaning of the double pole structure of  $\Lambda(1405)$ . There is minor model dependence of the  $\Lambda(1405)$  pole positions within the chiral unitary approach [12]. The higher pole, which dominantly couples to  $\bar{K}N$ , has less model dependence in the pole position, located around 1420 MeV, because it is constrained by well-observed  $\bar{K}N$  scattering data, while the lower pole strongly coupling to  $\pi\Sigma$  has strong model-dependence due to lack of  $\pi\Sigma$  scattering data. This implies that the  $\bar{K}N$  scattering data alone cannot determine the full structure of  $\Lambda(1405)$ , and data for the  $\pi\Sigma$  scattering, such as the scattering length and effective range, are necessary to investigate the structure of  $\Lambda(1405)$  further [13].

Dominance of  $\bar{K}N$  in the  $\Lambda(1405)$  resonance could be seen in the nonmesonic decay of  $\Lambda(1405)$  in nuclear matter [14]. Figure 2 shows possible one-meson exchange diagrams for the  $\Lambda^*N \rightarrow YN$  ( $Y = \Lambda$  or  $\Sigma$ ) transition. Since, according to the SU(3) flavor relation of the meson-baryon couplings, the  $\eta NN$  and  $\bar{K}N\Sigma$  couplings are small, the  $\bar{K}$  ( $\pi$ ) exchange is dominated in the  $\Lambda^*N \rightarrow \Lambda N$  ( $\Lambda^*N \rightarrow \Sigma N$ ) transition. Therefore, the ratio of the transition rates of  $\Lambda^*N$  to  $\Lambda N$  and  $\Sigma N$  is strongly sensitive to the  $\Lambda^*$  coupling strengths to  $\bar{K}N$  and  $\pi\Sigma$ . The form factor of  $\Lambda(1405)$  was also calculated within the chiral unitary approach using the chiral effective theory for the couplings of the external currents with the hadronic constituents [7, 15]. The density distributions and mean-



**FIGURE 2.** Diagrams for  $\Lambda^* N \rightarrow Y N$  transition in one meson-exchange model [14]. The left two diagrams is for  $\Lambda^* N \rightarrow \Lambda N$  and, the right two for  $\Lambda^* N \rightarrow \Sigma N$ .

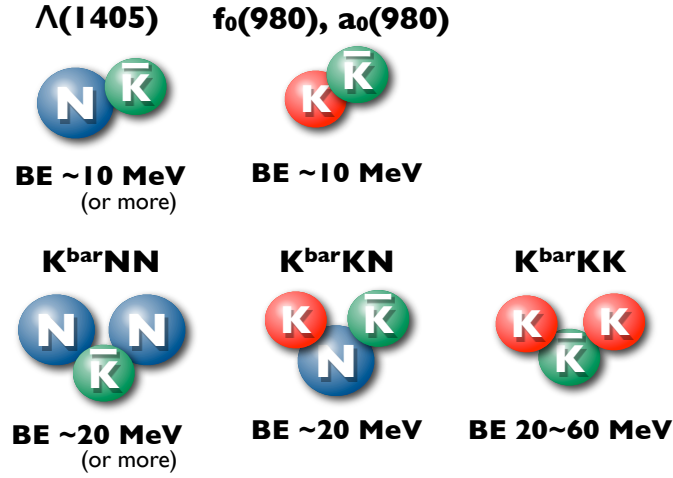
squared radii were calculated from the form factor [15]. The electric radius of  $\Lambda(1405)$  at the pole position is obtained as a complex number  $-0.157 + 0.238i \text{ fm}^2$ , whose modules is much larger than that of neutron. This implies that kaon spreads spatially in wide range around nucleon. It is also interesting seeing the  $\Lambda(1405)$  resonance in the SU(3) limit [6], to see the role of the flavor symmetry in dynamically generated resonance. In a SU(3) flavor limit in which the octet mesons and baryons have averaged masses, there are two bound states with 70 MeV and 5 MeV binding energies in the flavor single and octet channels, respectively. These binding energies are smaller than typical SU(3) breaking scale,  $\sim 150 \text{ MeV}$ , and therefore the SU(3) breaking effects should be larger than the low lying hadrons. This is a different aspect from constituent quark models.

## KAONIC FEW-BODY SYSTEMS

As we discussed above, it is most probable that  $\Lambda(1405)$  is a dynamically generated resonance of a meson and a baryon, and especially one of the states can be a quasi-bound state of  $\bar{K}N$ . Such a quasibound state is called as hadronic molecular state. Hadronic molecular state is a (quasi) bound system composed of hadronic constituents which keep their identity as they are in isolated systems, appearing just below the threshold of break-up into the constituent hadrons. Driving force to make hadronic molecular states is hadronic interaction rather than inter-quark dynamics and confinement force. Thus, inter-hadron distances inside the hadronic molecular states are larger than the typical size of the low-lying hadrons which is characterized by the quark confinement range. Nucleus, which is a bound system of baryons, is also classified into this category.

Here let us consider hadronic molecular states with kaon and nucleon constituents. For hadronic molecular states, pion has a too light mass to form bound states with other hadrons by hadronic interaction, since the pion kinetic energy in a confined system by hadronic interaction overcomes attractive potential energy. In contrast, kaon plays a unique role in hadronic molecular state due to Nambu-Goldstone boson nature and its heavier mass. Chiral effective theory suggests  $s$ -wave attraction in the  $\bar{K}N$  and  $\bar{K}K$  channels, which is enough strong to form two-body quasibound states. The mass of kaon is so moderately heavy that kaon kinetic energy in hadronic bound systems can be smaller. In kaonic few-body systems, hadronic molecular states are unavoidably resonances decaying into pionic channels.

In chiral dynamics the fundamental interaction is given by chiral effective theory,



**FIGURE 3.** Family of kaonic few-body states. The binding energies are calculated in chiral dynamics.

and for  $s$ -wave interaction, the Tomozawa-Weinberg interaction is a driving force of the hadronic molecular system. It is an interesting fact that the strength of the Tomozawa-Weinberg interaction is given by SU(3) flavor symmetry and  $K$  and  $N$  are classified into the same state vector in the octet representation. Therefore, the fundamental interactions in  $s$ -wave are very similar in the  $\bar{K}K$  and  $\bar{K}N$  channel. Consequently in these channels with  $I = 0$ , there are quasibound states of  $\bar{K}K$  and  $\bar{K}N$  with a dozen MeV binding energy. This similarity between  $K$  and  $N$  is responsible for systematics of three-body kaonic systems,  $\bar{K}NN$ ,  $\bar{K}KN$  and  $\bar{K}KK$ , as shown Fig. 3.

The celebrated  $\bar{K}NN$  state with  $I = 1/2$  can be classified into the kaonic few-body family. This state was originally suggested by [16, 17], and recent theoretical investigations shows that the  $\bar{K}NN$  system is bound with a large width in spite of discrepancy between theoretical predictions of the mass and width. A study based on chiral dynamics predicts smaller binding energy around 20 MeV [18]. For further investigation it is extremely important to understand coupled-channel effects of  $\pi\Sigma$  to the  $\bar{K}NN$  system. If it gives significant contribution, especially it is probable for a larger binding case, one should treat  $\pi\Sigma$  as a dynamically active channel. For this purpose, one needs more precise data on two-body  $\pi\Sigma$  scatterings [13].

The  $\bar{K}KN$  and  $\bar{K}\bar{K}N$  states with  $I = 1/2$  and  $J^P = 1/2^+$ , which are  $N^*$  and  $\Xi^*$  resonances, respectively, were studied first in Refs. [19, 20] with a single-channel non-relativistic potential model. The  $\bar{K}KN$  system was found to be bound with 20 MeV binding energy [19], and later was investigated in a more sophisticate calculation [21, 22] based on a coupled-channels Faddeev method developed in Refs. [23], in which a very similar state to one obtained in the potential model was found. Recently the  $\bar{K}KN$  state was found also in a fixed center approximation of three-body Faddeev calculation [24]. The  $\bar{K}KN$  state is essentially described by a coexistence of  $K\Lambda(1405)$  and  $f_0(980)N$  [19]. An experimental search for  $\bar{K}KN$  was discussed in Ref. [25].

The  $\bar{K}KK$  state with  $I = 1/2$  and  $J^P = 0^-$ , being an excited state of kaon, was studied in a two-body  $f_0K$  and  $a_0K$  dynamics [26], in the three-body Faddeev calculation [27]

and in the non-relativistic potential model [27]. The three-body Faddeev calculation was done in coupled-channels of  $K\bar{K}K$ ,  $K\pi\pi$  and  $K\pi\eta$  and a resonance state was found at 1420 MeV, while the potential model suggested a quasi bound state with a binding energy 20 MeV. This state is essentially described by the  $\bar{K}KK$  single channel and its configuration is found to be mostly  $f_0K$ . Experimentally, Particle Data Group tells that there is a excited kaon around 1460 MeV observed in  $K\pi\pi$  partial-wave analysis, although it is omitted from the summary table.

In the potential model calculations of the  $\bar{K}KN$  and  $\bar{K}KK$  states, it was found that the root mean-squared radii of these systems are as large as 1.7 fm, which are similar with the radius of  $^4\text{He}$ . The inter-hadron distances are comparable with an average nucleon-nucleon distance in nuclei. It was also found that the two-body subsystems inside the three-body bound state keep their properties in isolated two-body systems. These features are caused by weakly binding of the three hadrons, for which the  $KN$  and  $KK$  repulsive interaction plays an important role to form hadronic molecular states.

## SUMMARY AND OUTLOOK

We have discussed the structure of the  $\Lambda(1405)$  resonance in chiral dynamics. We have found that the  $\Lambda(1405)$  resonance can be described by meson-baryon dynamics. Due to the presence of two attractive channels in fundamental meson-baryon interactions the observed  $\Lambda(1405)$  resonance is composed by two pole states. One of the states is a quasi-bound state of  $\bar{K}N$  located at around 1420 MeV and dominantly couples to the  $\bar{K}N$  channel. Thus, this is the relevant resonance for the kaon-nucleus interaction. This finding is completely a consequence of chiral dynamics with constraint from the  $K^-p$  scattering data, not a theoretical ansatz nor one putting by hand, unlike Ref. [17] in which the  $\Lambda(1405)$  position, 1405 MeV, is an input. The double pole structure of  $\Lambda(1405)$  can be confirmed experimentally by observing  $K^-d \rightarrow \Lambda(1405)n$ , in which  $\Lambda(1405)$  is produced by the  $\bar{K}N$  channel and the peak position appears around 1420 MeV.

The idea that  $\Lambda(1405)$  is a quasibound state of  $\bar{K}N$  can be extended to further few-body states with kaons like  $\bar{K}NN$ ,  $\bar{K}KN$  and  $\bar{K}KK$  having dozens MeV binding energy. In these states, a unique role of kaon is responsible for the systematics of the few-body kaonic states. Kaon has a half mass of nucleon and a very similar coupling nature to nucleon in the  $s$ -wave chiral interaction. This leads to weakly bound systems within the hadronic interaction range. The hadronic molecular state is a concept of weakly binding systems of hadron constituents. If a resonance state has a large binding energy measured from the break-up threshold, coupled-channel effects, like  $\pi\Sigma$  against  $\bar{K}N$ , and/or shorter range quark dynamics may be important for the resonance state. In such a case the hadronic molecular picture is broken down, and one should take into account the coupled channels contributions and quark dynamics for the study of the structure.

For some specific hadronic resonance, hadrons themselves can be effective constituents. The hadronic molecular configuration is a complementary picture of hadron structure to constituent quarks, which successfully describe the structure of the low-lying baryons in a simple way. Strong diquark configurations inside hadrons can be effective constituents [28], and mixture of hadronic molecular and quark originated states is also probable in some hadronic resonances [29]. The hadronic molecular state has a larger

spacial size than the typical low-lying hadrons. In heavy ion collision, coalescence of hadrons to produce loosely bound hadronic molecular systems is more probable than quark coalescence for compact multi-quark systems [30]. Thus, one could extract the structure of hadrons by observing the production rate in heavy ion collisions.

## ACKNOWLEDGMENTS

The author would like to thank his collaborators for their collaborations on the works presented here. This work was supported by the Grant-in-Aid for Scientific Research from MEXT and JSPS (Nos. 22740161, 22105507). This work was done in part under the Yukawa International Program for Quark-hadron Sciences (YIPQS).

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